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Mechanical vibration measurement

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MECHANICAL VIBRATION MEASUREMENT

EDWARD PATRICK APPERT

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MECHANICAL VIBRATION MEASUREMENT

by

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This work is accepted as fulfilling

the thesis requirements for the degree of

MASTER OF SCIENCE

in

MECHANICAL ENGINEERING

from the

United States Naval Postgraduate School.

In the calibration of mechanical vibration pickups the accuracy
of the calibration depends upon how accurately the displacement of
the pickup can be measured.

This thesis has been a study into the feasibility of calibrat-
ing vibration pickups by means of an optical interferometer system.
The unit used in the study was designed by Professor E. K. Gatcombe
in 1952 and work was done by this author from January 1953 through
May 1953 at the United States Naval Postgraduate School, Monterey,
California.

The author is indebted to Professor Gatcombe for his valuable
guidance throughout the entire work and to Professor C. H. Kalmbach
for his helpful assistance. Grateful acknowledgement is due to Joe
Oktavec for the excellence of the machine work involved.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

TABLE OF SYMBOLS AND ABBREVIATIONS

d   Distance between optical flats.

n   An integer greater than zero.

λ Wavelength of light source.

φ Angle of incidence and refraction.

$\overset{o}{A}$ Angstrom units. $1 \overset{o}{A} = 10^{-8}$ cm.

mm   Millimeters.

a   Acceleration of pickup in "g".

ω Frequency of vibration in radians per second.

r   Amplitude of vibration in inches.

CHAPTER I

SUMMARY

1. Introduction.

An important consideration in the employment of a seismic
pickup is the accuracy and reliability of the criteria set up to
evaluate the response characteristics of the instrument.

In the calibration of any seismic pickup the accuracy of the
calibration will be directly dependent on how accurately one knows
and can describe the motion imparted to the pickup.

The methods generally employed for applying a known motion to
the pickup are:

(1) Mechanical Methods

(2) Transfer Function Methods

(3) Secondary Standard Methods.

The mechanical method and the transfer function method are
adequate for calibrations over a narrow frequency range. Standard
references are available delineating the limits of these methods.

2. Objective of this thesis.

This thesis is an investigation into the use of an optical
secondary standard of displacement for a seismic pickup, specific-
ally as applied to the development of an accelerometer pickup.

3. General Methods Employed.

Reference to figure 1 will show the schematic arrangement of
the components employed in the test setup. These components include
a mercury lamp, filters, a collimating lens, silvered optical flats,
a condensing lens, a field stop, a photoelectric tube, and a means
of visual presentation of the output of the phototube.

Oscilloscope

Phototube

Field Stop

Camera Lens

Moving Optical Flat

Stationary Optical Flat

Collimonating Lens
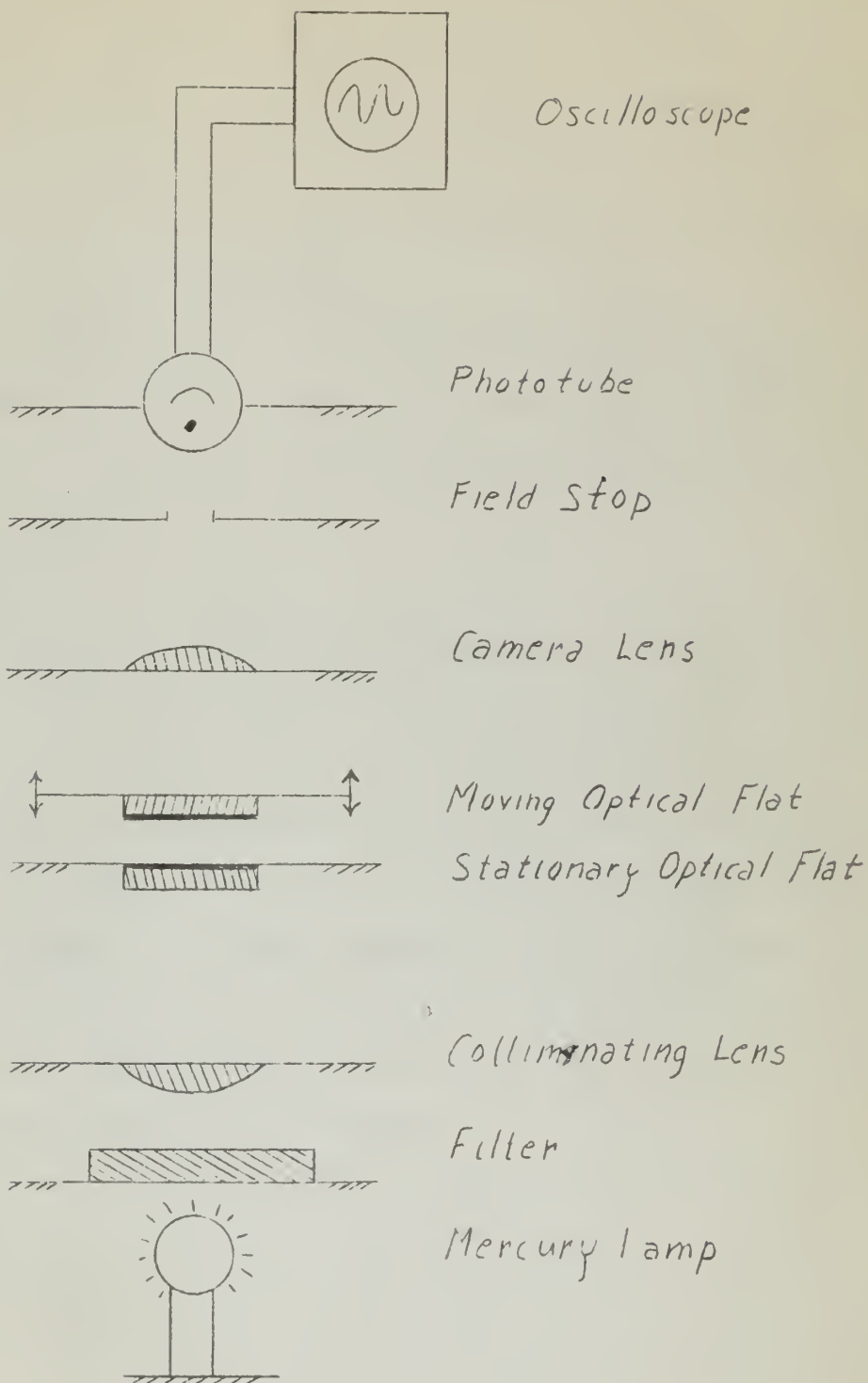
Filter

Mercury lamp

Figure 1

When the optical flats are made parallel (by external adjustments) the image of the extended source reflected in the air film between the two plane silvered flats produces the well known Haidinger fringes. A displacement of one optical flat by an amount equal to half a wavelength of the monochromatic light source will cause the central image of the fringe pattern to undergo one cyclic change as from dark to light. By proper adjustment of the optical stop and the phototube the change in the central dot will be recorded on the cathode ray oscilloscope.

In the test setup the moving optical flat is vibrated by an electromagnetic vibration inducer. The oscilloscope indicates the changes in the displacement of the optical flat per cycle of the vibration inducer.

4. Findings.

The interferometer principles provide an excellent method of measuring displacements. In the calibration of pickups the calibration curve of the pickup and the amplitude response curve may be readily obtained. The apparatus is complex to build, but extremely stable once adjusted. The success of the unit is indicated by its ability to operate over a wide frequency and amplitude range.

Critical design features are the method of keeping the optical flats parallel during vibration of the moving flat, and maintaining the stationary flat without any motion.

THEORY OF INTERFEROMETER OPERATION

The employment of Haidinger fringes in the Fabry-Perot inter-
ferometer is generally studied in an undergraduate course in optics.
A brief review of the principle is given here to refresh the prin-
ciples in the minds of the readers so that the design problems in-
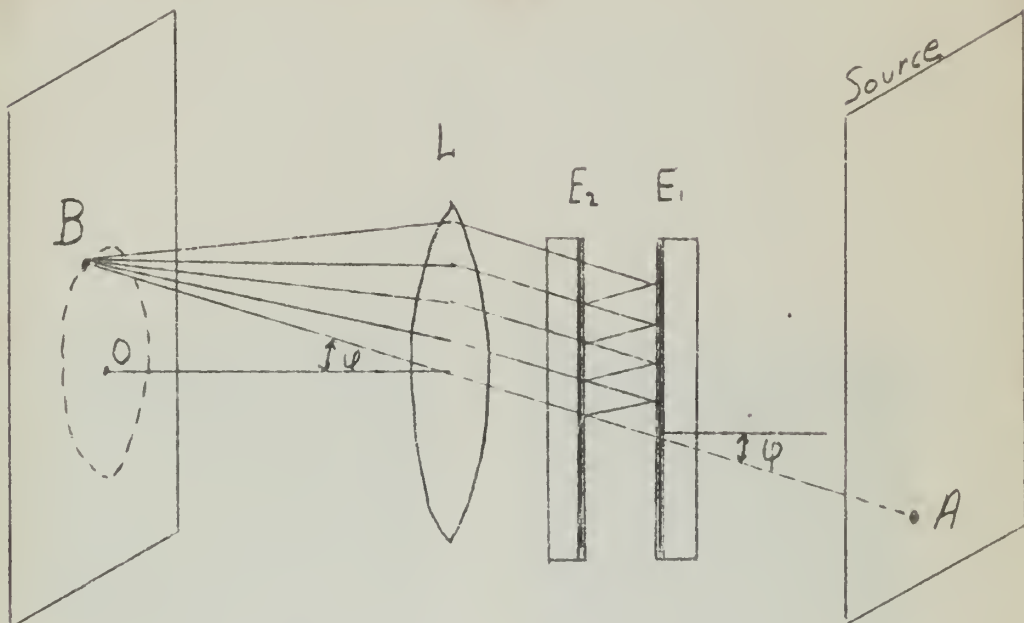volved may be understood.

Figure 2

A monochromatic light ray from point A on the extended source
transverses the silvered optical flats EE. Since the flats are par-
allel the multiple reflected emergent beams are all parallel to the
direction of the incident ray. If the emergent beams are collected
by lens L, they form at point B a part of a Haidinger fringe pattern.

4

The condition for reinforcement of the transmitted rays in air is:

$$2d \cos \varphi = m \lambda$$

This condition will yield a circle at O the intersection of the axis of the lens with the screen. The circle diameters are proportional to the focal length of the image-forming lens and inversely as $\sqrt{d}$, where d is the separation of the two flats. Altering the distance between the flats by one-half the wavelength of the light source will cause the central image of the Haidinger fringes to complete one cycle of change of the light intensity (from light to dark in the case of figure 3).
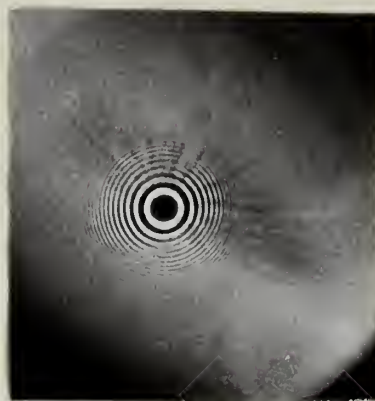

Figure 3

DESIGN CONSIDERATIONS AND CHANGES REQUIRED

1. Original Unit.

The unit as designed by Professor Gatcomb consisted of: a Hanovia mercury light source, two quartz optical flats surfaced on the plane side with aluminum film, camera and collimating lenses of 38 mm focal length, a field stop and an RCA 1-P-42 vacuum photoelectric tube. Reference to figure 1, page 2, shows the arrangement of the components.

This original unit failed to function properly for numerous reasons, each of which will be taken up under the heading of the component involved.

2. Mercury Light Source.

The obvious choice for monochromatic light in interferometry is the green light of the mercury arc with a wavelength of 5461Å. The mercury light source is readily available as are the required filters to render the light almost perfectly monochromatic. These advantages outweigh the disadvantages of lowered intensity when higher frequencies and the reduced response of commercial photocells to this wavelength.

In operation of the unit the Hanovia mercury light failed to operate satisfactorily. The bulb being of the high pressure design rapidly heated up and introduced pressure broadening effects which caused the Haidinger fringe pattern to disappear. This problem was rectified by the purchase from the R & K Company of Pasadena, California of a special low pressure mercury light arranged in a

flat spiral. Care was taken in the design of the bulb that it could withstand any vibration forces that might be encountered in the calibration tests. A high intensity light is desired since the greater the intensity of the monochromatic light source the stronger the signal produced by the photoelectric tube. The space limitations of the calibration unit restricted the size of the A & H light to one of about 40 watts.

3. Quartz Flats.

Three important design considerations are associated with the quartz flats, viz: the sharpness of the fringes observed, the intensity of the light which arrives at the phototube, and the size of the central image at the optical stop. The successful operation of the unit depends upon satisfying these highly critical and mutual dependent requirements.

The sharpness of the fringes (distribution of intensity) has been set in classical form by Airy (Reference 3). In figure 4 is shown the intensity contours for the Haidinger fringes, showing how their sharpness depends upon the reflecting power. When the mirror surfaces reflect between 80 to 90% of the incident light the bright fringes almost equal the incident light intensity, less absorption, while the dark fringes represent almost complete exclusion of the incident light.

As the reflecting coefficient approaches 100% the fringe sharpness improves, but the intensity of the light received by the phototube becomes too low to be effective. This consideration requires that the mutually contradictory factors of high reflection and high transmission be compromised. Figure 5 shows the relation
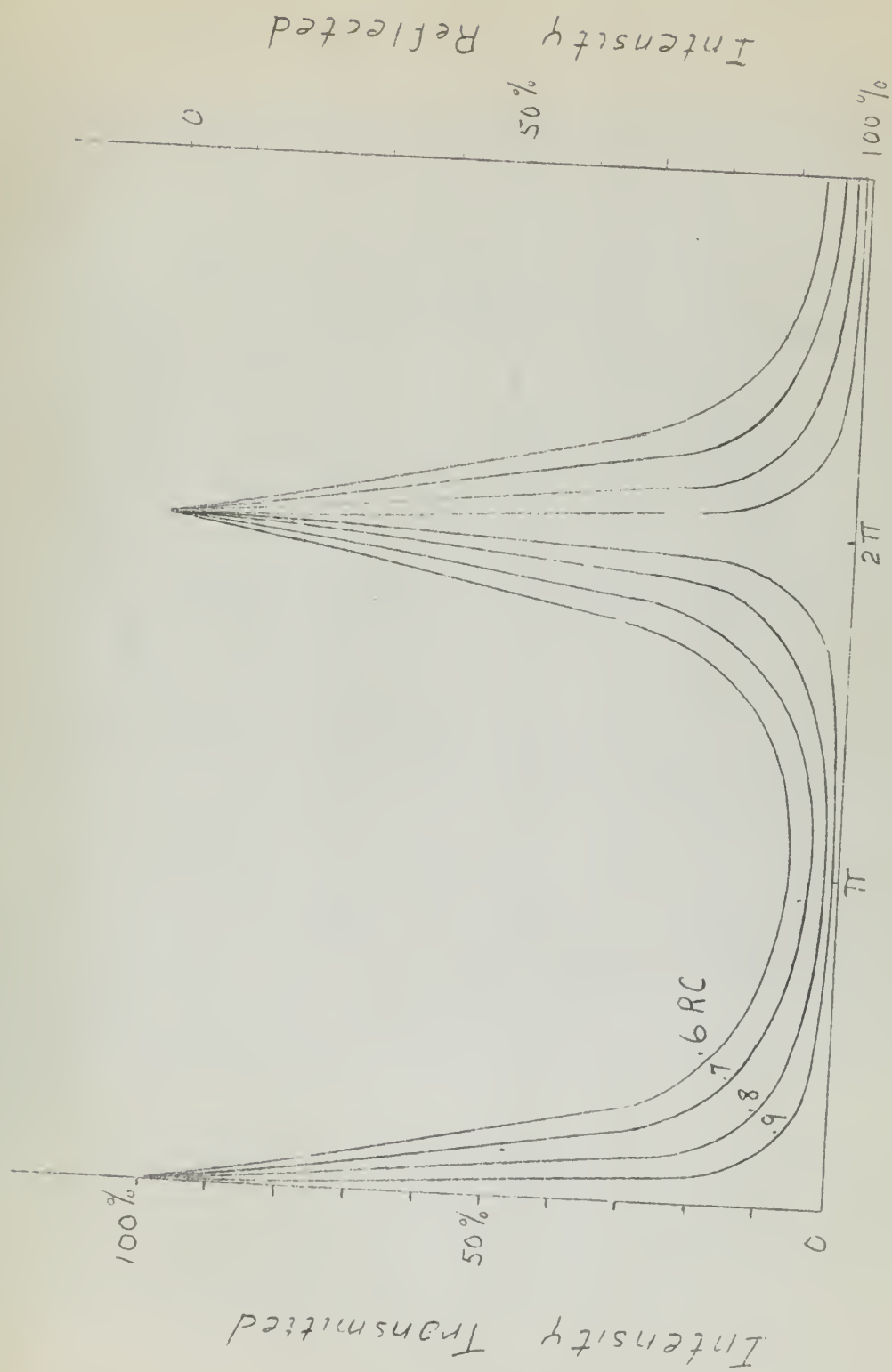
7
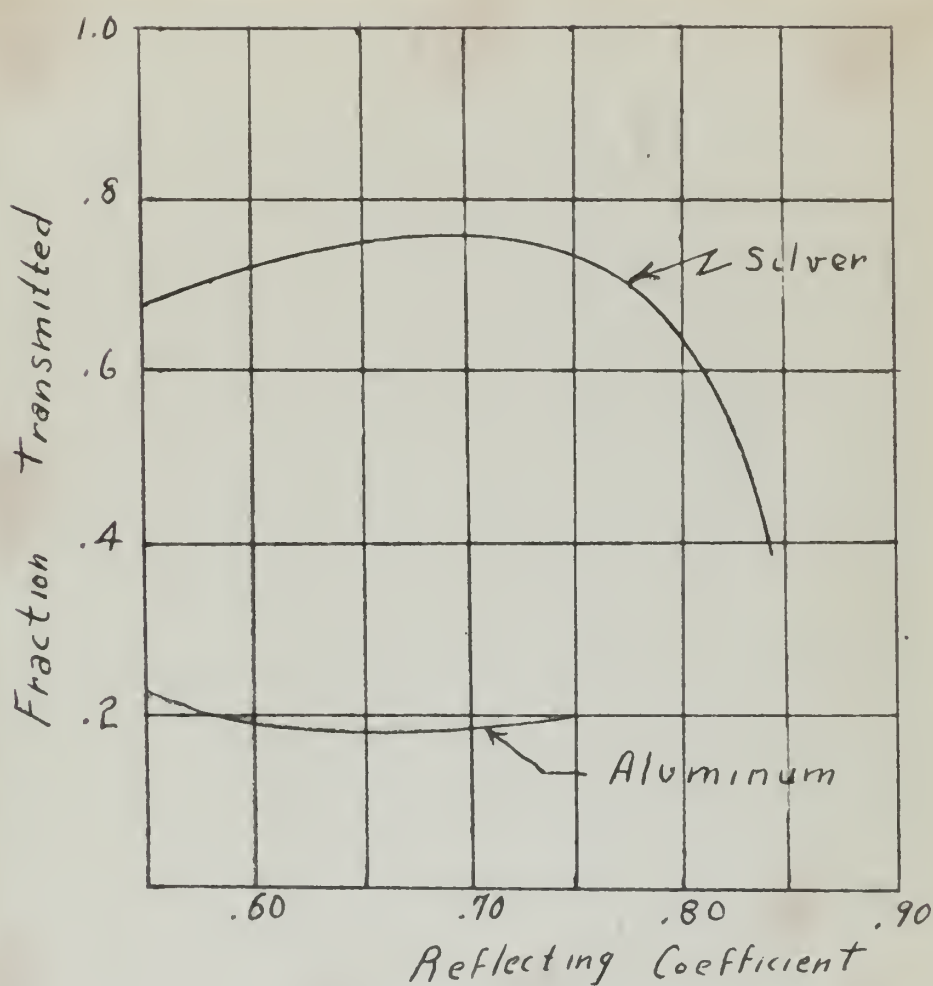
Figure 4

Figure 5

The quartz flats were prepared for silvering by the ionic bombardment technique. The silvering was performed by evaporating the silver from a tungsten filament under a vacuum of about 10^{-5} mm of Hg. To obtain optimum purity of the deposited silver thereby reducing absorption losses required the preparation of a large number of mirrors before acceptable ones were obtained.

The distance between the optical flats (d) in the original unit was 0.286 inches. This produced a central image at the focus of the condensing lens with a diameter of about 0.015 inches. In order to increase the diameter of this image the distance between the optical flats was decreased to 0.150 inches, resulting in an increase in the central image to 0.015 inches. The moving optical flat was designed to vibrate with a maximum amplitude of 0.0075 inches, giving a 100% factor of safety before flats would collide.

4. Photoelectric Tube.

The original unit was designed to utilize an RCA photoelectric tube 1-P-42. This tube was chosen for its response to the 5461 Å mercury light and its desirable size. It is only about 1 inch in length by $\frac{1}{4}$ inch in diameter with the photocathode at the end of its tubular structure. Figure 6 indicates the spectral response characteristics of the tube.

Reference again to figure 1 shows that the tube is required to pick up the light passed through the field stop and forward it to the recording instrument. The tube performed this specific function satisfactorily, and did transmit a signal indicating a change in the central image from a bright to a dark image. However, even after the changes to the mercury light and to the optical

10

flats the intensity of the light which the phototube received re-
sulted in a current flow of the order of 10^{-10} amperes. This
current flow was so low that it was difficult to distinguish be-
tween the noise of the electronic equipment and the signal output
of the phototube. Since the unit as originally built left no room
for a larger phototube, the entire physical structure of the
assembly was changed to accommodate a photomultiplier tube.

The photomultipli-
chosen, the RCA 1-1-21,
has the same spectral
response as the 1-1-42
(figure 6). This tube
is capable of producing
a maximum current ampli-
fication of 2,000,000 at
an applied voltage of
100 volts per stage.
Since amplification was
now accomplished in the
phototube, the reduc-
tion in the noise level
resulted in a relatively
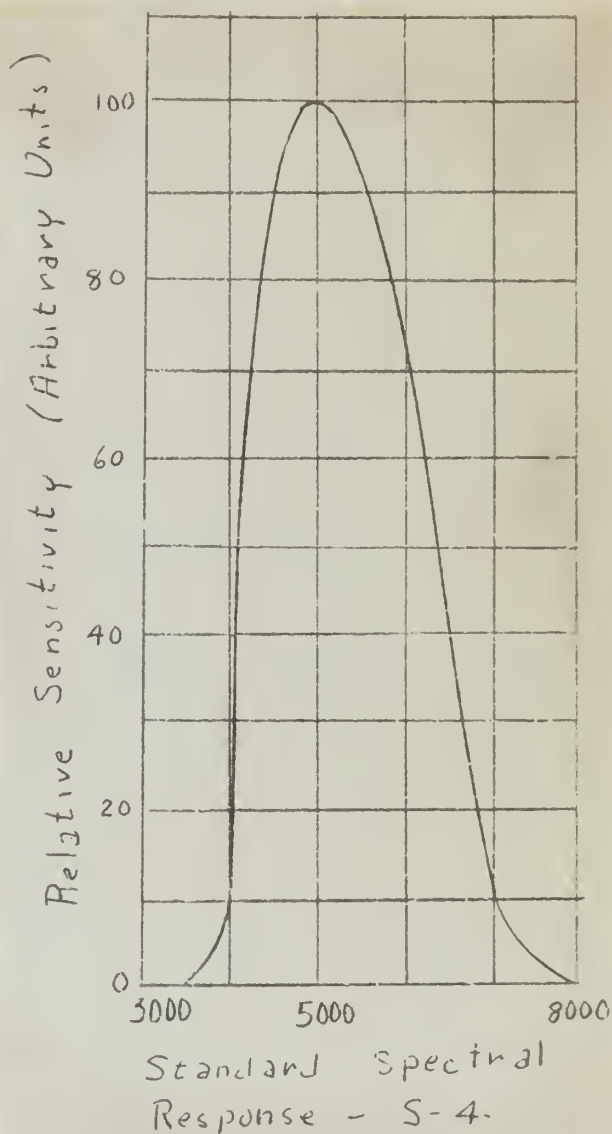low noise to signal
ratio at the recording
instrument.

Standard Spectral
Response – S-4.

Figure 6

11

1. Phototube Output.

    Each time the separation between the optical flats is changed
by one-half of the wavelength of the mercury light source the cen-
tral image of the Haidinger fringe completes one cyclic change.
For the mercury line 5461Å this corresponds to a change of
0.00001071 inches in the separation of the plates. If the moving
optical flat is vibrating at 1000 cycles per second through an
amplitude of 0.0001 inches the phototube will be acted upon by a
change in light cycles equal to

$$4 \times 1000 \; \frac{0.0001}{0.00001071} \qquad \text{or} \quad 37355 \text{ cycles per second.}$$

2. Accelerometer Output.

    If an accelerometer is attached in some manner to the moving
optical flat this amplitude and frequency would correspond to an
acceleration of:

$$1 \qquad a = r\omega^2 = \frac{0.0001}{12} \times (1000 \times 2\pi)^2 = 328g$$

    Correlation of the accelerometer output with the output of
the phototube yields a true calibration for the accelerometer.

3. Presentation of the Outputs.

    Figure 8 shows the test setup. The output of the phototube
is displayed on the Y axis of the Cathode Ray Oscilloscope. When
the time sweep of the oscilloscope is made equal to the one vibra-
tion of the unit, the number of peaks on the curve in one cycle
will equal the number of changes in distance between the optical
flats in units of half wave lengths of light. See figure 7. By

12

this method one may
immediately deter-
mine the amplitude
of displacement
occurring in an
accelerometer which
vibrates through
the same displace-
ment as the moving
optical flat.

$2 \frac{5}{6}$ CYCLES
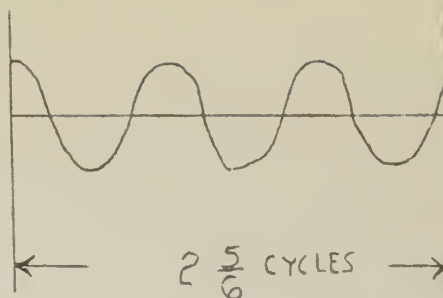
Interferometer Output

Figure 7

CHAPTER V

RESULTS

1. Test Runs.

Figure 5 shows a composite of photographs taken during test runs. The runs were made at several frequencies and amplitudes of vibrations. The variation of the central image is super-imposed on a 60 cycle wave. By utilizing the 60 cycle wave as a time base, and knowing the frequency of vibration one may readily count the "pips" and ascertain the number of halfwave length changes in displacement between the optical flats.

Had a D.C. mercury light source been used the time base could be the frequency of the vibration. The photographs would then be as in figure 7. Lack of a 3000 volt D.C. supply voltage prevented the author from using this more direct approach.

2. The Test Unit.

The unit used in this investigation easily complied with all the criteria by which we judge a measurement standard:

  a. It has a wide frequency and amplitude range.

  b. It is extremely stable as regards time, temperature and rugged use.

  c. It does not introduce any harmonic distortion.

  d. The output is related to the mechanical motion only.

  e. It is simple to use and easy to calibrate.

3. Accelerometer Calibration:

The accelerometer calibration is obtained by recording the voltage across the bridge circuit of the transducer in the commercial type strain gage accelerometer. Calibration curves

14

obtained directly are: (1) amplitude of vibration vs. accelerometer
output at constant frequency and (2) frequency vs. accelerometer
output per "g". No calibration runs were actually made.

1.   Feasibility of the Method.

The author is of the opinion that an optical standard for
the measurement of small displacements can be successfully em-
ployed to calibrate seismic pickups to an accuracy of within
one percent. (See appendix I). The unit used in the thesis
work is extremely stable and capable of operation over a wide
range of frequencies and amplitudes. As with any unit of a
new design there are features which require further study and
improvement to make the unit more than an experimental laboratory
test piece. Of particular importance is to reduce the degree of
mechanical coupling between the moving flat and the stationary flat,
and to increase the intensity of the mercury lamp.

2.   Suggestions for further study.

Improvements in the electronic arrangements for the calibra-
tion tests are a fertile field of study. The limitations of thesis
time prevented building special circuits for measuring the outputs
involved. Of great value in the calibration would be a circuit to
record transient variations in the displacement and in the acceler-
ometer output. The study of transient accelerometer measurements
represents a field all too long neglected, and this unit coupled
with an electron counting circuit would afford a comparatively
direct means of investigating the phenomenon.

APPENDIX I

ERROR CONSIDERATIONS

Assume the output of the phototube as shown by the scope is
9 5/6 cycles of a sine wave pattern. For mercury light of 5461 Å
the displacement of the plate is: $9\ 5/6 \times \dfrac{5461}{2}$ or 26845 Å.

If the number of cycles on the scope is read to the nearest 30° the
accuracy of the measurement is plus or minus 1/24 the oscilloscope
cycle or 114 Å.

The error for this displacement (about .0001 inches) corres-
ponds to: $\dfrac{114}{26845}$ or 0.42%.

Obviously for smaller displacements the errors are larger
and vice versa.

Another source of error is in the frequency measurements.
There are available standards of frequency measurement accurate
to within 0.1% or less, so that this error is almost negligible.

In actual work one might anticipate slightly higher errors,
possibly due to slight vibrations of stationary optical flat. How-
ever, it is not anticipated that the error would total more than
1% in any measurement made.
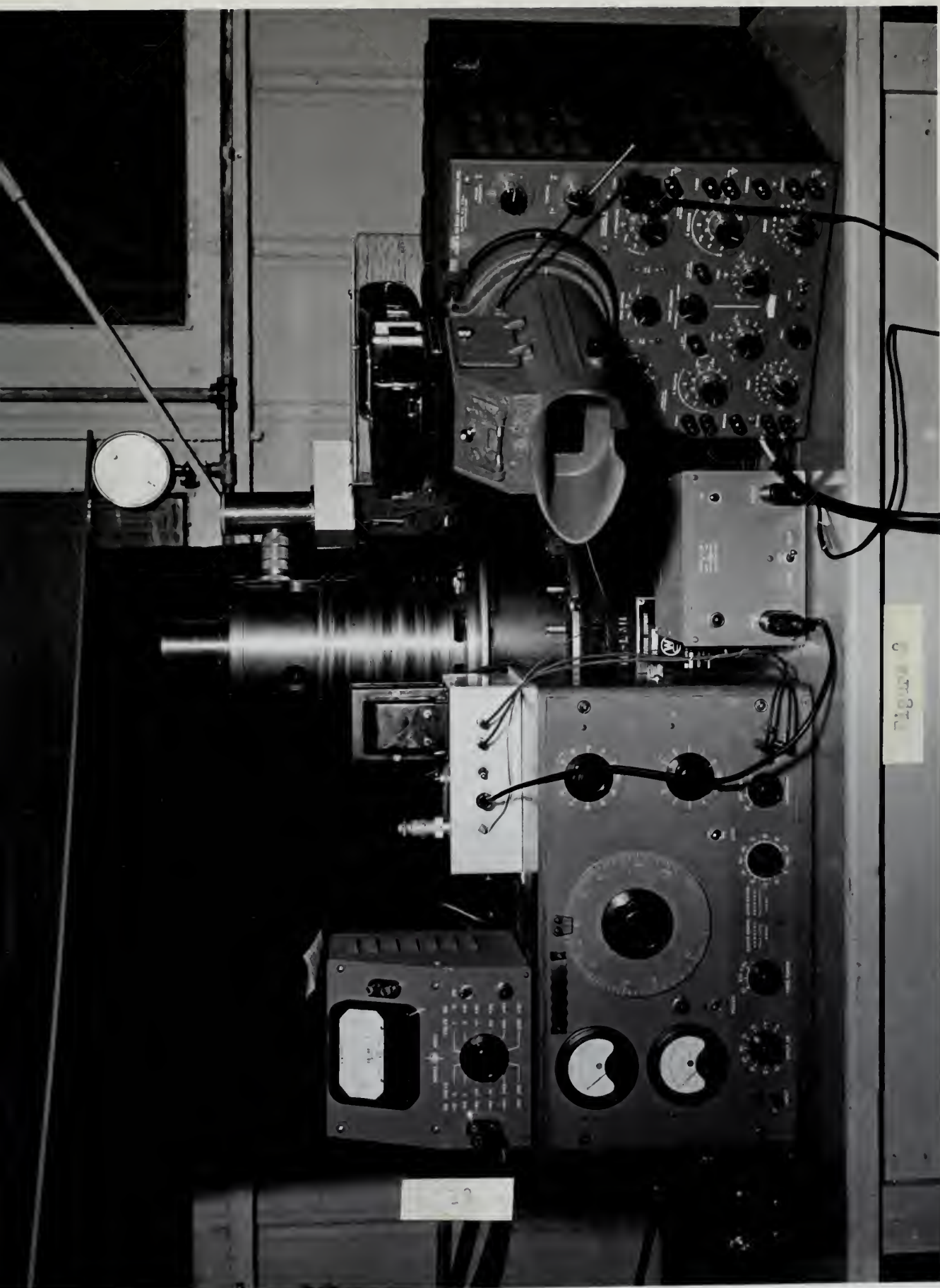
17

Figure 10

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62